TITLE: DFB Laser Diode with Variable Diffraction Grating Period

Ioffe Institute
6th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 22–26, 1998.

DFB laser diode with variable diffraction grating period

G. S. Sokolovskii, A. G. Deryagin and V. I. Kuchinskii
Ioffe Physico-Technical Institute RAS, Polytechnicheskaya 26, St.Petersburg, Russia

Single-mode semiconductor DFB lasers are considered to be an optimal light sources for optical communicational and information processing systems. DFB lasers with first order corrugation demonstrate the best threshold characteristics. However, "classical" first-order DFB laser has noncontrollable corrugation phase at the laser facets and, because of this, poor single longitudinal mode operation yield.

In 1976 Haus and Shank [1] have proposed and theoretically investigated DFB laser with tapered structure. They have shown that coupling and Bragg parameter variations along the laser structure remove the threshold degeneracy of the 1-st order DFB lasers and cause light generation exactly at the Bragg frequency. It is important to notice that coupling and Bragg parameters variations can be obtained not only by the effective refractive index variation, but by the corrugation period (Λ) modulation as well.

The simplest case of the antisymmetric taper DFB is the coupling and Bragg coefficients step at the centre of the DFB structure. Such a step can be created by the insertion of the quater-wave section (λ/4) between two equal uniform DFB structures. Experimentally $\lambda/4$-shifted DFB lasers demonstrate single-mode generation only near threshold current and even for small pumping currents ($I > I_{\text{th}}$) "spatial hole burning" in the ($\lambda/4$-shift region causes spectrum degeneration from single-mode to multimode.

To obtain DFB laser with sufficiently more uniform light intensity distribution along the active region (i.e. with greatly reduced "spatial hole burning") we propose to use tapered structure caused by the variation of the refractive index modulation period along the laser structure.

Diffraction grating was created by the holographic photolitography method. Holographic photoresist exposure procedure was carried out according to the "corner" scheme (Fig. 1a). The argon laser ("Spectra-physics-2020", $\lambda_0 = 0.3511\,\mu$m) after widening and spatial filtration illuminated the sample and the mirror, fixed at the 90° as regards to each other. Interferention pattern period "Λ" was determined by the angle of the "corner" turn according to the relation:

$$\Lambda = \frac{\lambda_0}{2\sin\alpha} \tag{1}$$

where $\alpha = 0$ corresponds to the normal angle of the light incidence on the sample.

For the creation of the diffraction grating with variable period we propose to use the "corner" scheme with sufficient illumination beam divergence. Generally, some grating period variation takes place always, but usually (long distance from the "corner" to pin-hole and small distance from the sample to the centre of the "corner") it is less than 0.01 Å/cm, and the grating period is accurately given by the expression (1).

But for the significantly reduced l, the strongly increased coordinate dependence of the grating period is observed. The grating period dependence on the y coordinate

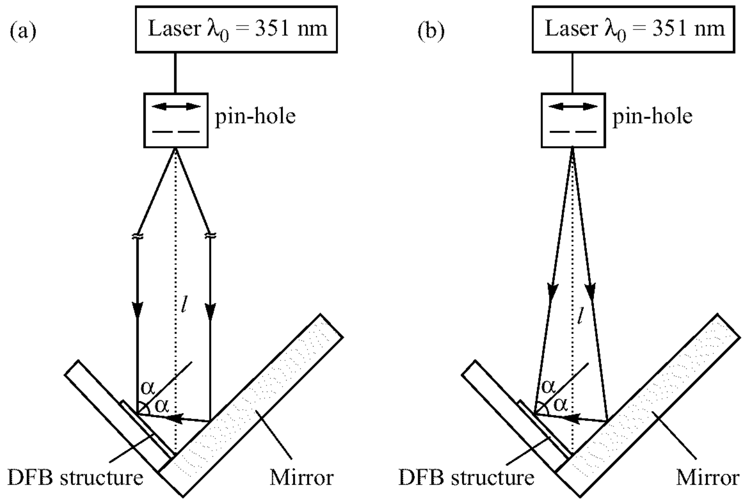

Fig 1. The "corner" scheme of holographic photolitography.

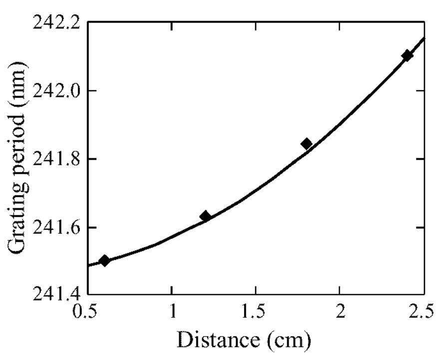

Fig. 2. Grating period vs distance from the centre of the "corner" for the "corner" scheme of holographic photolithography for $\lambda_0 = 351.1$ nm, $\alpha = 46.64°$ and $l = 40$ cm.

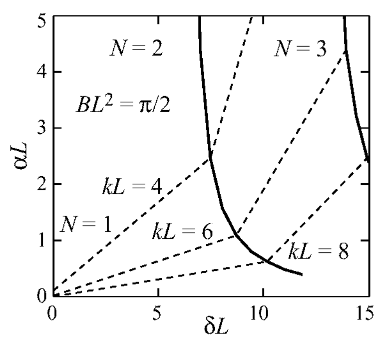

Fig. 3. The approximate gain coefficients vs frequency deviations with DFB coupling as a parameter for DFB structure with variable grating period.

(perpendicular to the grooves of the grating) is given by the following expression:

$$\Lambda = \lambda_0 \left(\frac{l \sin\alpha + y}{\sqrt{l^2 + 2yl \sin\alpha + y^2}} + \frac{l \sin\alpha - y}{\sqrt{l^2 - 2yl \sin\alpha + y^2}} \right)^{-1} \tag{2}$$

where l is the distance from the pin-hole to the centre of the "corner".

In the present work we have used $\times 80$ ($F = 0.5$) microobjective for the beam widening and the 15 μm pin-hole for the spatial beam filtration. We have obtained good quality diffraction gratings with 0.24 μm grating period, 0.1–0.15 μm corrugation depth and up to 0.5 Å/cm grating period variation.

According to [1] Bragg deviation for the tapered DFB structure is expressed as follows: $\delta(y) = \beta - [(\pi/\Lambda(y)]$. Unfortunately the expression (2) is too complicated for the direct substitution. It can be significantly simplified by expressing the coordinate y

as the sum $y = Z_0 + z$. This transition must be understood as follows. The distance from the centre of the "corner" to the considered point y is the sum of the distance from the centre of the "corner" to the centre of the laser Z_0 and the distance from the centre of the laser to the considered point z: $Z_0 \gg z$; $l \gg Z_0$. Using this condition and

$$\lim_{x\to 0} \frac{1}{\sqrt{1 \pm x}} = 1 \mp \frac{x}{2} \tag{3}$$

and neglecting the small terms of the second order one can obtain:

$$\beta(z) = \frac{\pi}{\Lambda(z)} = \frac{\pi}{\Lambda_0} - Bz \tag{4}$$

where

$$\Lambda_0 = \frac{\lambda_0}{2\sin\alpha[1 - 2(Z_0^2/l^2)]} \qquad B = \frac{\pi}{\lambda_0}\frac{8Z_0 \sin\alpha}{3l^2}. \tag{5}$$

We consider the medium with quasiperiodical corrugation of refractive index:

$$n(z) = n + n_1 \cos\left[2\beta(z)z\right]. \tag{6}$$

The system of differential equations for coupled waves R and S in this case is as follows:

$$-(\mathrm{d}R/\mathrm{d}z) + [\alpha - \mathrm{i}\delta(z)]\, R = \mathrm{i}k(z)S$$

$$(\mathrm{d}S/\mathrm{d}z) + [\alpha - \mathrm{i}\delta(z)]\, S = \mathrm{i}k^*(z)R \tag{7}$$

$$\delta(z) = \beta - \beta(z) = \delta_0 + Bz, \quad k(z) = k_0 \exp(\mathrm{i}Bz^2) \tag{8}$$

where δ_0 is the Bragg deviation at the "centre" of the structure — the "effective" Bragg deviation and k_0 is the "effective" coupling:

$$\delta_0 = \beta - \beta(0) = \frac{n\omega}{c} - \frac{\pi}{\Lambda_0}, \quad k_0 = \frac{\pi n_1}{\Lambda_0}. \tag{9}$$

It must be noted, that the "effective" coupling and Bragg deviation are the values of these parameters for the convenient DFB structure. Note, that at the frequency matched to the centre of the frequency gap of the DFB laser with diffraction grating period Λ_0, Bragg deviation becomes the antisymmetrical function of the distance. The last means that this case is particular and the frequency $\omega = \pi c/n\Lambda_0$ is the centre of symmetry of the threshold gain spectrum of the DFB laser with variable diffraction grating period.

Substituting (8) in (7) one can obtain for $R(z)$ and $S(z)$:

$$R'' - \mathrm{i}2BzR' + \left(3B^2z^2 + \mathrm{i}4Bz + \mathrm{i}B - k_0^2 - \alpha^2\right) R = 0 \tag{10}$$

$$S'' + \mathrm{i}2BzS' + \left(3B^2z^2 + \mathrm{i}4Bz - \mathrm{i}B - k_0^2 - \alpha^2\right) S = 0 \tag{11}$$

where $\alpha = \alpha + \mathrm{i}\delta$ is the gain coefficient. Estimation of the gain coefficients for different modes of DFB laser with variable diffraction grating period is the ultimate aim of this work.

The particular solutions of (10) and (11) are:

$$r(z) = \exp\left(\frac{\mathrm{i}Bz^2}{2}\right) D_\nu(\xi_r), \qquad s(z) = \exp\left(-\frac{\mathrm{i}Bz^2}{2}\right) D_{-\nu}(-\xi_s) \tag{12}$$

where $\nu = \mathrm{i}k_0^2/4B$, $\xi_r = 2z\sqrt{\mathrm{i}B} - \alpha/\sqrt{\mathrm{i}B}$, $\xi_s = 2z\sqrt{-\mathrm{i}B} + \alpha/\sqrt{-\mathrm{i}B}$.

To obtain the gain coefficients it is possible to analyze the considered structure on the computer or to use the perturbation approach providing the physical insight into the behaviour of DFB structures with variable grating period. In the limit of low-gain and high Q the threshold gain is inversely proportional to the external Q-factor of the resonant transmission mode [1].

$$2\alpha = \frac{\omega_0}{v_g}\frac{1}{Q_{\mathrm{ext}}} \tag{13}$$

where ω_0 is the frequency of the resonant mode, v_g is the group velocity, and external Q-factor is:

$$\frac{1}{Q_{\mathrm{ext}}} = \frac{P_s}{\omega_0 W} \tag{14}$$

where P_0 is the output power of the resonant mode according to the first order of perturbation approach, and W is the energy accumulated by the structure:

$$P_s = |R_0 + \Delta R|^2 - |S_0 + \Delta S|^2 \Big|_{z=-L/2}^{z=L/2}, \; W = \frac{1}{v_g}\int_{-L/2}^{L/2} |R_0|^2 - |S_0|^2 \,\mathrm{d}z. \tag{15}$$

In our case the grating period variation is small in comparison to the step of diffraction grating. Hence, the amplitudes R and S variation from these amplitudes for the uniform grating is small. Thus we can put the zero-order amplitudes R_0 and S_0 equal to the solutions for the convenient DFB laser with zero loss:

$$S_0 = \pm A \sinh\left[\gamma\left(z \pm \frac{L}{2}\right)\right], \qquad R_0 = \pm\frac{\gamma A}{\mathrm{i}k_0^*}\cosh\left[\gamma\left(z \pm \frac{L}{2}\right)\right], \qquad z \lessgtr 0 \tag{16}$$

where $\gamma = |k_0|$ is constant along the structure.

Using (6)–(9) and $|R_0| \approx |S_0|$, one can get:

$$\alpha L = \frac{|k_0|L}{\sinh(|k_0|L) - |k_0|L}\left(1 + \frac{BL^2}{|k_0|L}\right). \tag{17}$$

The resonant frequencies and thresholds for the modes of higher orders can be obtained by the same procedure. In this case $\beta = \sqrt{\delta^2 - |k_0|^2}$ and

$$\alpha L = \left(\frac{2m\pi}{|k_0|L}\right)^2, \qquad \delta L = \pm\sqrt{(2m\pi)^2 + (|k_0|L)^2}. \tag{18}$$

Gain coefficients of DFB laser with variable period of diffraction grating defined by (17)–(18) with feedback efficiency $k_0 L$ as a parameter are represented in the Fig. 3.

The above calculations shows that the proposed DFB laser diode with variable period of diffraction grating has the single-frequency gain spectrum like a $\lambda/4$ laser and uniform light intensity distribution like the convenient DFB laser.

The work was done under the financial support of RFBR (grant No. 96-02-17864a).

References

[1] H. Haus, C. Shank, "Antisymmetric taper of distributed feedback lasers", *IEEE J. Quantum Electron.* **QE-12** No. 9, 532-539 (1976).